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Journal of Terramechanics 38 (2001) 133–151

Journal of Terramechanics

www.elsevier.com/locate/jterra

Soil compaction and over-winter changes to tracked-vehicle ruts, Yakima Training Center, Washington

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Abstract

We monitored two experimental areas at the Yakima Training Center (YTC) in central Washington to measure changes to M1A2 Abrams (M1) tank-rut surface geometry and in- and out-of-rut saturated hydraulic conductivity (K_{fs}), soil penetration resistance (SPR) and soil bulk density (BD). Profile-meter data show that rut cross-sectional profiles smoothed significantly and that turning ruts did so more than straight ruts. Rut edges were zones of erosion and sidewall bases were zones of deposition. K_{fs} values were similar in and out of ruts formed on soil with 0–5% moisture by volume, but were lower in ruts formed on soil with about 15% water. Mean SPR was similar in and out of ruts from 0- to 5-cm depth, increased to 2 MPa outside ruts and 4 MPa inside ruts at 10- to 15-cm depth, and decreased by 10–38% outside ruts and by 39–48% inside ruts at the 30-cm depth. Soil BD was similar in and out of ruts from 0- to 2.5-cm depth, and below 2.5 cm, it was generally higher in ruts formed on moist soil with highest values between 10- and 20-cm depth. Conversely, BD in ruts formed on dry soil was similar to out-of-rut BD at all depths. This information is important for determining impacts of tank ruts on water infiltration and soil erosion and for modifying the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP) models to more accurately predict soil losses on army training lands.

Keywords: Tank ruts; Soil compaction; Profile-meter; Saturated hydraulic conductivity; Penetrometer; Bulk density; Yakima Training Center

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0022-4898/01/$20.00
PII: S0022-4898(00)00017-3

1. Introduction

Heavy tracked vehicles create ruts, compact soils and disturb vegetation, thereby increasing the potential for erosion. Ruts can concentrate surface water flow, depending on orientation, slope, soil characteristics and landscape position [6,30]. The geometry of hillslope channels, such as rills or ruts, is important because it influences the velocity and thus erosivity of water flowing in it [5,9]. Soil compaction affects erosion by changing the stability and size distribution of soil aggregates, and increasing soil bulk density and penetration resistance [9,26]. Small increases in soil bulk density can result in disproportionately large decreases in infiltration rates, that increase the potential for runoff [16]. Vehicle traffic can physically disrupt vegetation [12,14,22], but may also indirectly impact plant growth by altering nutrient availability, soil physical characteristics and patterns of soil moisture storage [2,31].

Wind and water erosion (with cycles of wetting and drying and freezing and thawing) modifies rut geometry and ameliorates soil compaction [8,9,21,26]. As it thaws, frozen wet soil becomes temporarily weakened with a low resistance to erosion [7,13]. Freeze–thaw effects may be especially important in cool semiarid locations such as the Yakima Training Center (YTC) located in central Washington (Fig. 1), where the majority of precipitation occurs from late fall to early spring [18], coinciding with times of soil freezing. Information about how freeze–thaw cycles affect the shape and the degree of soil compaction in tank ruts is important for assessing impacts of ruts on water infiltration and soil erosion. In addition, soil erosion models such as the Revised Universal Soil Loss Equation (RUSLE) [28] and the Water Erosion Prediction Project (WEPP) [27] can incorporate this information to more accurately predict soil losses on army lands in cold climates.

This research is part of a USA-CRREL/USDA-ARS project to determine soil freeze–thaw effects on hydraulic geometry, soil strength, infiltration, runoff erosivity and soil erodibility of vehicular ruts and natural rills. Our specific goals for this work were to record changes of tank rut surface shape over time and to measure indices of soil compaction in M1 tank ruts. Changes in rut geometry and degree of soil compaction are important to rut-flow hydraulics and erosion, and they can be readily measured by military land managers.

2. Research sites

We established two research sites 8 December 1995, within the boundaries of an ongoing tracked vehicle impact model (TVIM) study, managed by YTC personnel [14]. We chose these sites because they represent conditions common on the YTC, were accessible, had uniform vegetation and soil, and information about the date of rut formation and antecedent soil moisture was available (Russell Fitzgerald, YTC, personal communication).

The YTC encompasses an area over 130,000 ha in the Columbia basin of south central Washington (Fig. 1). The region is part of the shrub-steppe, the largest of the grassland regions in North America [19]. Soils are typically loess overlying basalt

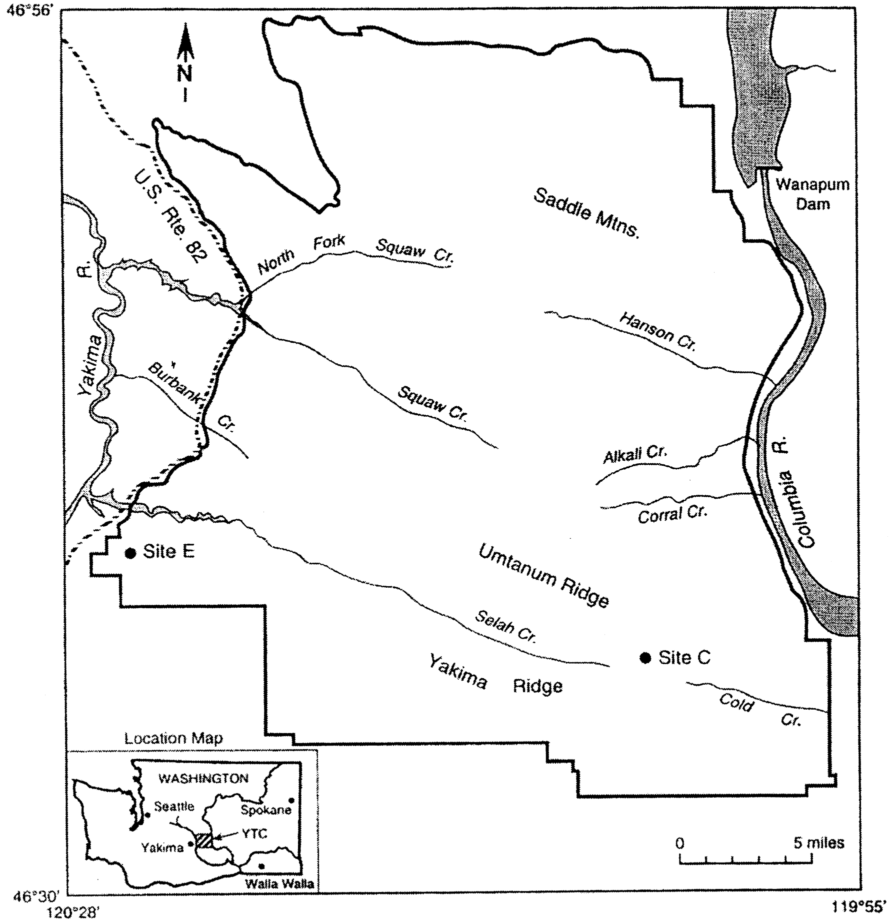

Fig. 1. Research sites, Yakima Training Center.

and the climate is characterized as semiarid, temperate, and continental with cold, wet winters and hot dry summers [14,18].

Site E, at about 450-m altitude, receives about 20 cm of precipitation annually. The soils and vegetation are typical for central Washington state: shrub-steppe consisting of deep silty clay-loam soils (Drysel, Meloza-Roza; fine, montmorillonitic, mesic Xeric Camborthids) on a 0–3% slope, and dominated by big sagebrush (*Artemisia tridentata*) [4,14]. Site C, at about 900-m altitude, has lower temperatures and about 30 cm of annual precipitation. Soils are Colockum-Benway, fine loamy, mixed, mesic Calcic and Aridic Calcic Argixerolls on a 1–3% slope. The dominant vegetation is perennial bunchgrass such as blue-bunch wheatgrass (*Elytrigia spicata*) or *Poa secunda*. Further details about vegetation at both sites are reported by Jones and Bagley [14].

Tank ruts examined during this study were formed by one to eight passes of an M1A2 Abrams combat tank in July 1994 or April 1995 as part of the TVIM study (Table 1). Jones and Bagley [14] provide more details on site layout. The M1 has a listed vehicle weight of about 63,000 kg (69.5 tons) yielding a ground pressure of 1.08 kg/cm^2 (15.4 psi) [10]. We concentrated most of our measurements on ruts formed in April 1995 when soil water content was about 15% (by volume) in the top 10 cm (moist) because we observed little surface rutting in locations where tracks were formed in July 1994 when soil water was 0–5% (dry) (see also [26]).

3. Measurement and analytical methods

3.1. Rut profiles

We established 23 rut surface profile locations across ruts at site C and 21 at site E (Fig. 2). At site C, we measured profiles across straight ruts formed by 2 or 4 tank passes (6 replicates each) and across turning ruts formed by 1 or 2 passes, (6 and 5 replicates, respectively). At site E, we measured profiles across straight ruts formed by 2 or 8 tank passes (6 replicates each) and across 3 turning ruts formed by 1 pass (9 replicates in all).

We drove a 1-m length of steel rebar into the soil outside of the tank rut at both ends of a profile location to serve as a stable foundation for repeated measurements with a profile-meter such as described in McCool et al., [15] (Fig. 3).

The profile-meter is composed of a 1.83-m aluminum frame that supports 145 free-sliding, vertical aluminum-alloy pins arranged in a line on 1.27-cm spacing. The frame is held perpendicular to the soil surface by folding aluminum arms that also house a camera. To measure the rut, the profile meter is placed onto the rebar, and the frame is leveled using a bubble level so that the pins point directly down. The aluminum pins are carefully lowered onto the soil surface taking care that each is in contact with the

Table 1
Data on TVIM ruts that we measured[a]

Site	Rut name[b]	Number of passes
C	T-2	2
	T-4	4
	TURN 1	2
	TURN 2	1
E	T-2	2
	T-8	8
	TURN 1	1
	TURN 2	1
	TURN 3	1

[a] All ruts formed in April 1995, except E T-8, which was formed in July 1994.

[b] Soil water at time of tracking at T-8 was 0–5% (by weight); for all others it was 15%.

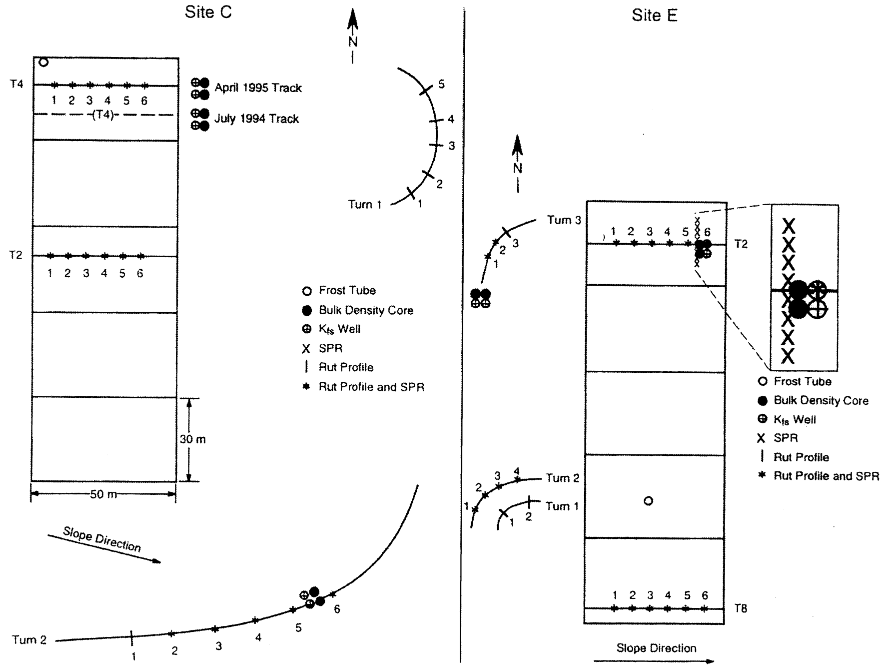

Fig. 2. Rut profile transect and soil property measurements locations; the symbol ⊕ indicates the approximate locations of Guelph permeameter wells, ● are soil cores to calculate bulk density (BD), and × indicates the location of soil penetrometer readings (SPR); drawing is not to scale.

soil surface. The details of the soil surface are shown by the height of the 145 aluminum pins against a scaled backdrop on the aluminum housing frame, which is photographed (Fig. 4).

We photographed each rut profile on 8 December 1995, 27 March 1996, 16 July 1996 and 1–2 April 1997. Each photo was digitized using SprintScan 35 (Polaroid) at a resolution of 1021 dots per inch (dpi) and archived as tagged image file format (tif) files. Digitized images were processed to correct for picture angle and exposure, and pin heights were measured using Sigmascan [23]. We excluded spurious pin height readings from the data set (<100) if we determined a pin had become suspended above the soil in the profile meter frame or had fallen into a crack in the soil. Some rut profiles at Site C (Turn 2) were obliterated after the second sampling.

We calculated the standard deviation of the 145 pin height readings from each rut profile photograph, as an indicator of surface roughness, and used these in subsequent analyses. We analyzed $\log_{10}$ transformed data with parametric statistics, like analysis of variance (ANOVA), and untransformed data with nonparametric statistics, such as the Kruskal-Wallis, Kolmogorov-Smirnov Two Sample and Friedman's tests. We included nonparametric statistics to relax classical assumptions about spatial and temporal independence of the data and about the shape of the sample distributions. Because tracking treatments were not identical at each site, we categorized

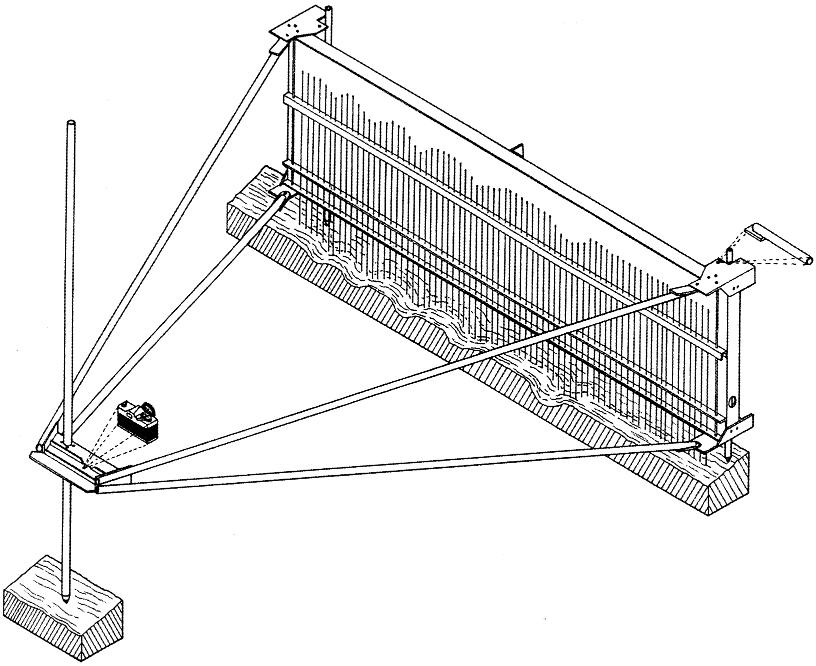

Fig. 3. Schematic of a portable photographically recording profile-meter (from reference [15]).

Fig. 4. Details of rut surface profile measured with the profile-meter.

data as either STRAIGHT-FEW (comprised of straight-path, 2-pass data from both sites), STRAIGHT-MANY (containing straight-path, 4-pass data from site C and 8-pass data from site E), or TURN-FEW (containing 1 or 2 pass, turning-path data from both sites). We analyzed data, collected on 8 December 1995, to determine the magnitude of the initial differences between the various tracking treatments. Differences were deemed statistically significant if Bonferroni adjusted probabilities were less than 0.05. Categorized data were further analyzed with a repeated measures ANOVA to determine if significant changes in rut profile smoothness occurred over time. All statistics were calculated using Systat 8.0 [24].

3.2. Soil properties

We measured snow depth and used a visual frost gauge [20] to estimate frost depth at each site during the 1995–1996 winter to establish baseline values for sites E and C.

On 1–3 May 1996 we measured saturated hydraulic conductivity (K_{fs}), soil penetration resistance (SPR) and bulk density (BD) in moist and dry-track locations at both sites (Fig. 2). We sampled compacted rut-soil and adjacent, uncompacted soil lying within 1 m of the center of ruts. We chose this distance because our initial measurements showed the zone impacted during tank trafficking extended less than 1 m out from the rut, and we stayed close enough to the rut to minimize the effects of natural spatial variability. The out-of-rut measurements were always made on the "out-facing" side of a rut, and not in the "shadow" of the tank pass, to avoid bias caused by dragging of the tank undercarriage over the soil.

We measured in situ K_{fs}, with a Guelph permeameter (Soilmoisture Equipment Corp.) to determine water infiltration into and through the soil, which would be useful for predicting rainfall infiltration and runoff [17]. We measured steady-state infiltration rates in standard 15-cm deep wells using 5 and 10 cm of head. From these rates we calculated K_{fs}, expressed in centimeters per second. We collected data in straight ruts and turning ruts at both sites (Fig. 2). Near the locations of these permeameter measurements, we also collected 5-×2.5-cm cores of soil at different depths to determine bulk density. At Site C we took 12 cores, every 2.5-cm from the soil surface to 30-cm depth; at site E, 6 cores every 5 cm. These cores were returned to the lab, weighed, dried at 105°C to a constant weight, and then used to calculate soil moisture content and bulk density (dry mass per unit volume).

We measured soil penetration resistance (SPR) to assess soil strength and density inside and outside of ruts as a function of depth close to many of the profile locations (Fig. 2). We quantitatively assessed spatial variability and "edge" effects by also measuring SPR every 15-cm along a 5.8-m transect perpendicular to site E rut T-2 between rut profiles 5 and 6. We used a hand-operated cone-type Bush recording soil penetrometer (Findlay, Irvine Ltd.), which measures the amount of force required to penetrate soil (e.g. [1,29]). The operator positioned the penetrometer perpendicular to the soil surface and pushed it into the soil with a steady force. We used the same operator and technique for all SPR measurements. The instrument measured SPR at 2-cm depth increments down to 30 cm and stored the information in an onboard data-logger.

4. Results and discussion

4.1. Frost depths

Table 2 lists snow accumulation and frost depths at various times. However, because frost depths were not read daily, these data do not show the number of freeze–thaw cycles at the two sites. The frost data indicate that the soil at site C froze deeper than that at E, although this difference diminished later in the winter; deeper frost at site C is expected because it is cooler than site E. One implication of a deeper frost depth is that possible freeze–thaw effects can extend farther into the soil profile at site C than site E. However, changes in soil compaction and rut profile may relate more to the number of freeze–thaw cycles than the depth of freezing. Both sites had days when a thawed layer of soil was observed between two frozen layers, indicating periods of partial, shallow thawing followed by refreezing. An important implication of deeper frost at site C is that water infiltration, from melting accumulations of snow in spring, may be impeded by a subsurface lens of ice for a longer time than at site E. If the soil moisture is already high in these soils, there will be increased potential for erosion from surface flow.

Table 2
Snow and frost depth

	Snow depth (cm)		Frost depth[a] (cm)	
Date	Site C	Site E	Site C	Site E
12-11-95	6	0	0.0–18.2	0.0
12-15-95	0	0	5.5–17.5	0.0
12-19-95	3	0	0.0–3.5, 6.0–15.5	0.0–3.7
12-21.95	0	0	0.0–4.0, 5.5–13.0	0.0
12-28-95	0	2	0.0–23.0	0.0–10.0
01-02-96	0	1	1.5–26.5	0.0–9.5
01-03-96	0	0	4.0–26.0	1.5–9.0
01-04-96	0	0	0.0–2.0, 5.0–26.0	0.0–9.0
01-05-96	0	Trace	0.0–26.0	0.0–1.5, 3.0–9.0
01-09-96	0	4	4.5–24.5	0–7.5
01-11-96	0	4	5.0–23.0	0–7.5
01-12-96	0	4	5.0–23.0	0–7.5
01-16-96	0	0	0.0	7.0–7.5
01-17-96	0	0	0.0–1.5	0.0
01-18-96	0	0	0.0–6.5	0.0
01-22-96	10	9	0.0–12.0	0.0–6.2
01-23-96	10	9	0.0–12.5	0.0–6.8
01-24-96	14	14	0.0–13.0	0.0–7.5
02-27-96	7	2	0.0–4.0	0.0–5.5
03-01-96	0	0	0.0–11.0	0.0–10.0

[a] Readings indicate the range of depths for frozen soil as recorded by a frost tube. Thus a reading of 0.0–3.7 indicates the soil was frozen from the surface to a depth of 3.7 cm. A reading of 0.0–1.5, 3.0–9.0 indicates the soil was frozen from the surface to a depth of 1.5 cm, unfrozen from 1.5 to 3.0 cm and frozen from 3.0 to 9.0 cm depth.

4.2. Rut profiles

A depressed, compacted zone characterizes M1 tank ruts at YTC, about 64 cm wide, formed as the passing tank compresses the soil (Fig. 5). The rut depressions typically range from about 2- to 15-cm depth and often reveal the details of tank track patterns. A combination of shallow-shear failure and unconfined compaction from the track can result in relatively steep rut sidewalls, capped by a lip raised as much as 10- to 20-cm above the adjacent, uncompacted soil. The soil surface outside this raised lip is uncompacted. Turning ruts sometimes exhibited an asymmetric profile with one lip more pronounced than the other lip.

Analysis of categorized data from the initial sampling date with parametric ANOVA and the Kolmogorov-Smirnov two-sample test yielded identical results. We observed no significant differences between site C or E with overall average rut standard deviation of 4.16 and 4.47 cm respectively. However, the average standard deviation for TURN-FEW rut profiles (5.63 cm) was significantly greater than for STRAIGHT-MANY (3.64 cm) rut profiles which was significantly greater than STRAIGHT-FEW (2.77 m) (Fig. 6). The interaction term between site and rut type was not significant indicating that individual comparisons of turning ruts and straight ruts between sites did not differ from the combined analysis.

Repeated measures ANOVA and its nonparametric analog, the Friedman test indicated that rut profiles smoothed during the measurement period. The average

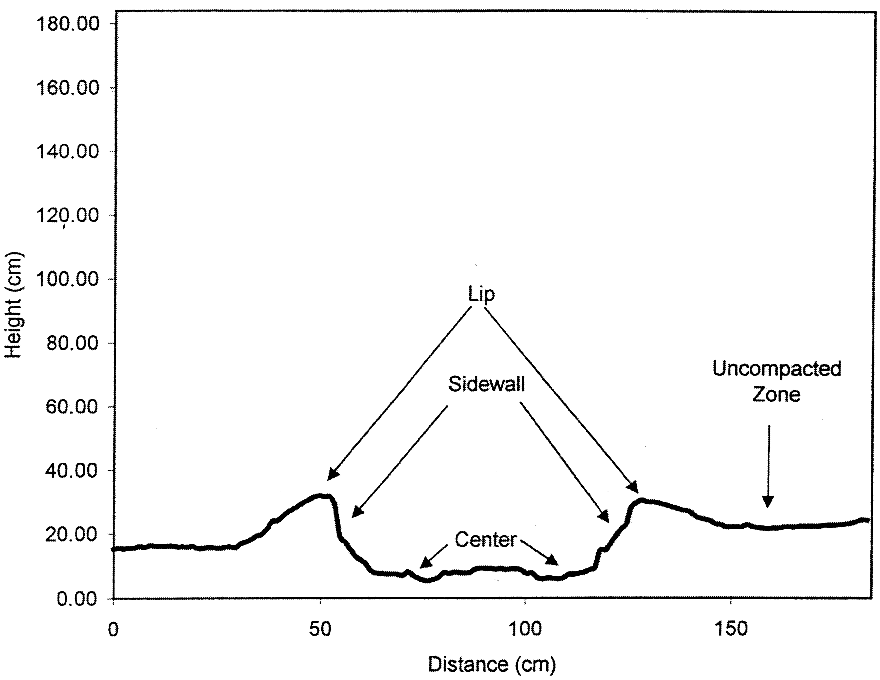

Fig. 5. General cross-sectional shape of an M1 Abrams tank rut.

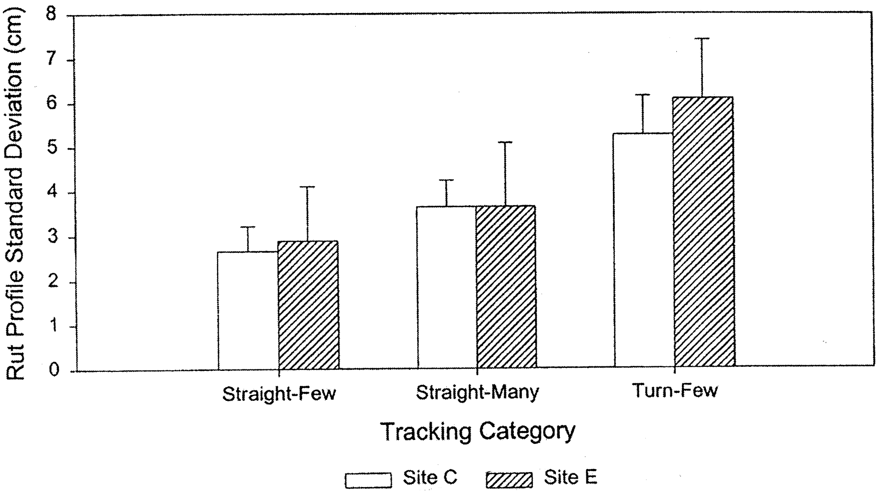

Fig. 6. Average rut profile standard deviation, with 95% confidence intervals, for data collected 8 December 1995 at Yakima Training Center WA. Data categories include: "Straight-Few", comprised of straight-path, 2-pass data from each site, $n=6$; "Straight-Many", containing straight-path, 4-pass data from site C and 8-pass data from site E, $n=6$; or "Turn-Few", containing turning-path, 1 or 2-pass, data from both sites, $n=9$–11.

standard deviation decreased significantly: 4.31 cm on 8 December 1995, 4.09 cm on 27 March 1996, 3.79 cm on 16 July 1996 and 3.68 cm on 1–2 April 1997. We examined the single-degree-of-freedom polynomial contrasts in the repeated measures ANOVA and found that there were significant differences in the rate (linear component) of smoothing among the three profile categories. Smoothing was significantly greater for TURN-FEW ruts than STRAIGHT-FEW or STRAIGHT-MANY ($P<0.01$). The single-degree-of-freedom quadratic contrast, in the repeated measures ANOVA, was also significant ($P<0.01$), meaning that the rates of smoothing were slowing with time (Fig. 7).

Changes in rut profile did not occur uniformly within the same rut. In general, the greatest changes in rut surface micro-relief occurred at the highest or lowest elevations of the rut profile (e.g. Fig. 8). A net loss of profile height was most often measured at the rut lip. In contrast, the base of the sidewalls of the ruts were the zones of deposition or infilling. Little change was detected along the steep sidewalls. However, the profile-meter can record only those profile changes that lie in an unobstructed vertical pin path. Careful field inspection showed that soil slumping sometimes resulted in concave or undercut rut sidewall geometry not detectable with this instrument.

Our profile measurements revealed inter- and intra-plot variability in rut shape and depth; not simply correlated with the number of vehicle passes. For example, there was no difference between ruts formed by 8 passes on dry soil at site E and ruts formed by 4 passes on moist soil at site C (the STRAIGHT-MANY category shown in Fig. 6). Turning ruts, formed from only 1 or 2 vehicle passes, had significantly greater standard deviations than straight ruts formed by 2, 4 or 8 passes. These

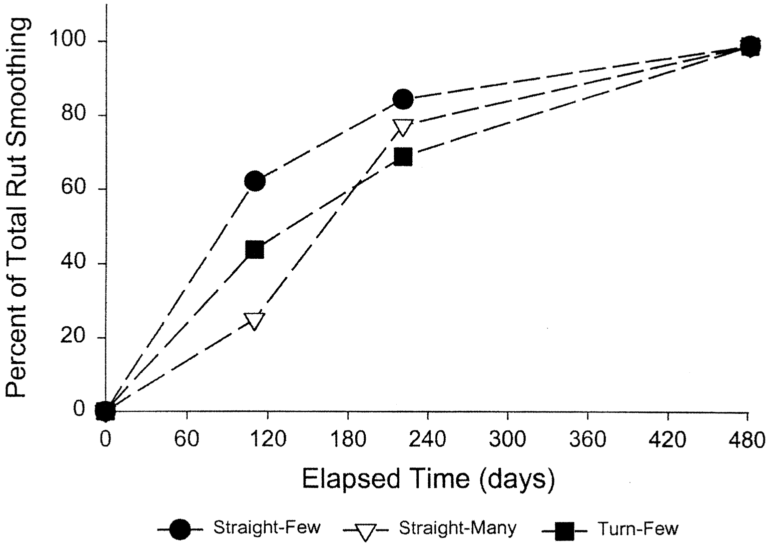

Fig. 7. Average % smoothing as a function of time. Data from both sites were combined into categories as described for Fig. 6.

patterns suggest that rut formation is strongly influenced by the path the vehicle travels and by antecedent soil moisture.

Another important source of rut surface variability was likely related to soil surface conditions and soil moisture at the time of measurement. We collected initial readings on 8 December 1995, when soil was locally frozen and partially covered by snow. The soil was near field capacity during our next readings on 27 March 1996. Our third set of readings, on 16 July 1996, were collected when the soil surface was dry, containing 0–5% water when shrink-swell cracks were evident. Our last readings were collected on 1–2 April 1997 when soil contained intermediate moisture. Accurate measurements require that the profile-meter support bars remain horizontally and vertically stable and that the reading pins rest exactly on the soil surface. Thus apparent changes in profile-meter measurements at a specific pin location may result from actual changes of the rut profile but will also reflect other mechanisms, such as frost heave or shrinking and swelling due to wetting-drying cycles, that shift the reference position (upright rebars). Also, the profile-meter pins may penetrate extremely dry, loose or wet soil and introduce an error into the profile readings. We observed this phenomenon in July 1996 for measurements in extremely dry soil at site E.

4.3. Saturated hydraulic conductivity, K_{fs}

Table 3 shows that soil compacted by the tank can have a reduced K_{fs} relative to the adjacent untrafficked soil. However, how much K_{fs} is reduced appears to be influenced by the amount of soil moisture at the time of tracking. For a location where tracks had been formed on moist soil at site C, the K_{fs} inside a rut was less

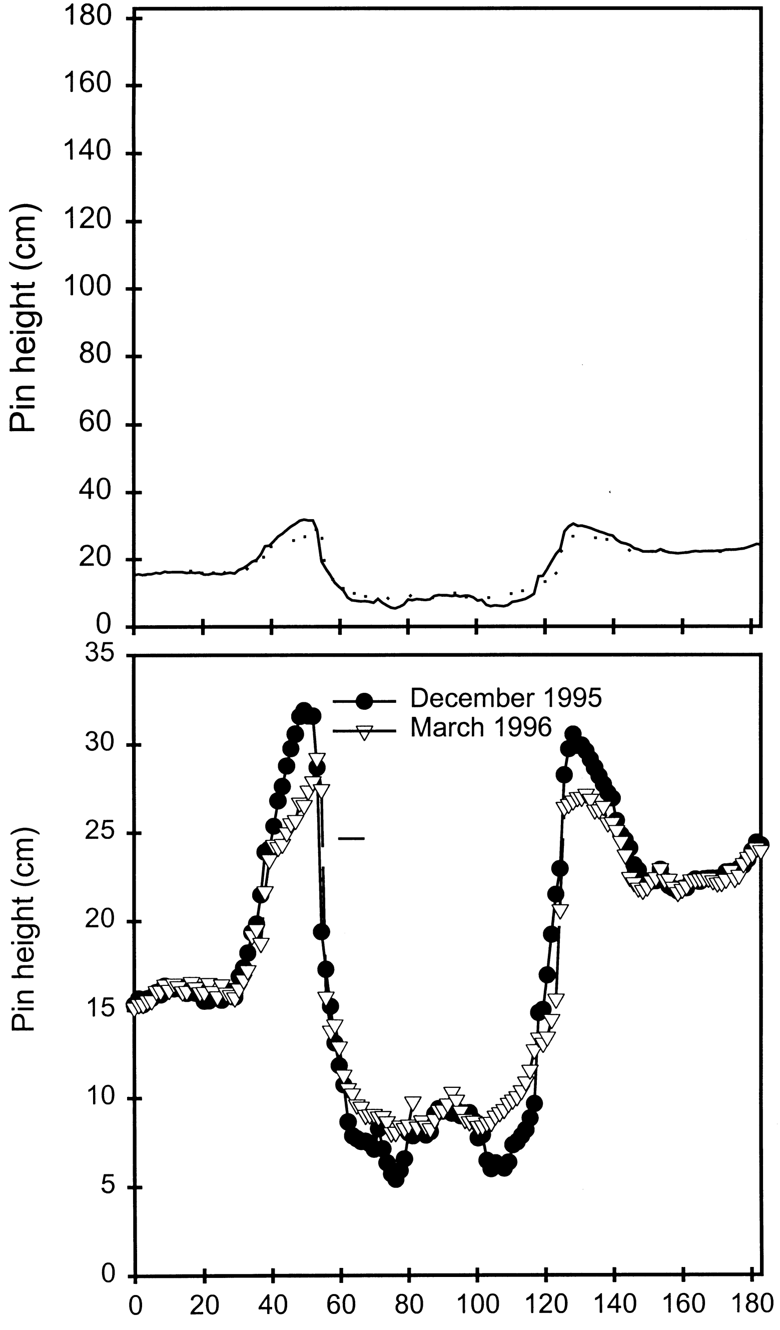

Fig. 8. Details of changes in tank rut surface profile over a 3-month period during the winter 1995–1996. The top figure shows the profile cross-section drawn to scale. The bottom figure shows the figure with an exaggerated vertical scale.

Table 3
Field saturated hydraulic conductivity, K_{fs}, measured 1–3 May 1996

Plot[a]	Out-of-rut K_{fs} (cm/s)	In-rut K_{fs} (cm/s)
Plot C, M1, ×4, moist, straight	4.14×10^{-4}	1.52×10^{-4}
Plot C, M1, ×4, dry, straight	4.68×10^{-4}	4.04×10^{-4}
Plot C, M1, ×1, moist, turn	4.29×10^{-4}	2.22×10^{-6}
Plot E, M1, ×2, moist, straight	1.86×10^{-4}	2.09×10^{-4}
Plot E, M1, ×1, moist, turn	1.91×10^{-3}	3.79×10^{-4}

[a] Plot nomenclature syntax is in the form of plot, vehicle type, number of passes, antecedent soil moisture at time of tracking and track path. Location notes refer to the map shown in Fig. 2.

than half that measured in adjacent uncompacted soil. Conversely, at a location where tracks had been formed on dry soil, the in-rut and out-of-rut K_{fs} was nearly identical. The K_{fs} rate measured outside a turning rut was comparable to values outside the two straight ruts, but K_{fs} was much lower inside the turning rut than in straight ruts. This suggests that the shearing and vertical forces generated during tank turning decrease the potential for subsequent water movement in the soil more than when a tank is moving straight.

Our measurements suggest K_{fs} is more spatially variable at site E than site C. The highest rate of K_{fs} (1.91×10^{-3} cm/s) was recorded in uncompacted soil on a small ridge less than 100 m from a location, where the uncompacted value was an order of magnitude less (1.86×10^{-4} cm/s). However, like site C, the K_{fs} observed at site E was lower inside a turning rut than out of rut. Unlike site C, little difference in K_{fs} was observed between a straight rut and adjacent uncompacted soil suggesting tank compaction did not affect potential for water movement at this location.

4.4. Soil penetration resistance, SPR

We observed similar in-rut and out-of-rut patterns of average penetrometer readings at both sites. Average SPR was low near the surface, increased significantly to maximum values between 10- to 15-cm depth, and then decreased significantly with depth at site C. (Fig 9). However, at E the average SPR in uncompacted soil did not decrease significantly with depth below the maximum.

More force is required to penetrate the soil in tank ruts than in adjacent uncompacted soil except near the soil surface. Average SPR was significantly greater inside ruts than outside ruts at all depths below 5 cm at site C and at depths between 7.5 and 22.5 cm at site E (Fig.9). SPR reached a maximum average value of about 4.0 MPa inside ruts, compared to about 2.0 MPa outside the ruts at both sites. Since plant roots may have difficulty penetrating soil at SPRs greater than about 3 Mpa (e.g., [11,25]), establishment of new seedlings in tank ruts may be impacted. Jones and Bagley [14] reported significant changes in plant community composition at these sites following tracking.

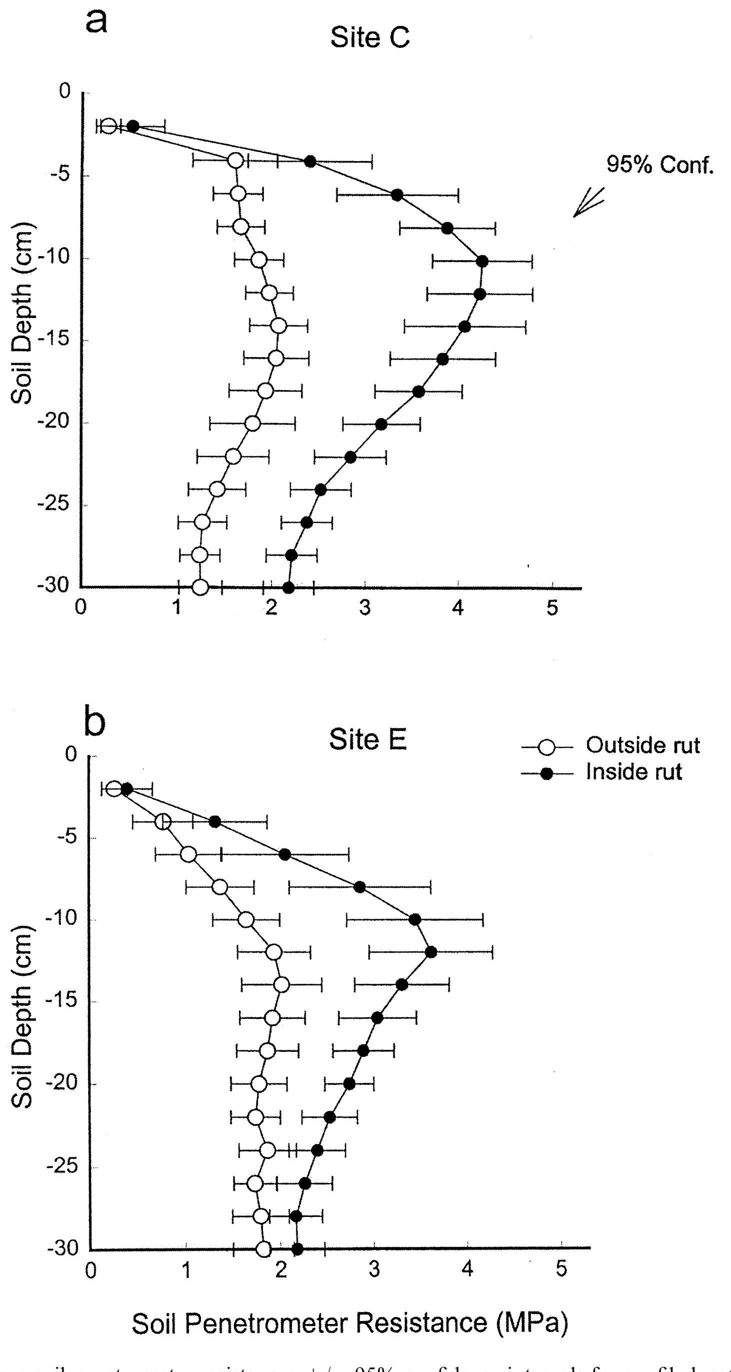

Fig. 9. Average soil penetrometer resistances +/− 95% confidence intervals for profile locations [$n=17$ (site C), 18 (site E)].

The average SPR profiles for each plot were useful for summarizing data and for statistical comparison between sites but did not reveal details about intersite variability. Some individual locations, within the sites, showed little change with depth or difference between rutted and uncompacted soil. Further, while we observed maximum average SPRs at 10- to 15-cm depth in both sites, turning ruts at site E exhibited simple increasing SPR with depth.

Average SPR profiles, delineated simply as inside or outside of ruts, did not reveal details of spatial variability such as would be encountered in the field. Fig. 10 shows a series of SPR profiles, measured every 15-cm across both ruts at T-2 of site E (see Fig. 2). It shows how SPR can vary greatly with small increments of depth or across short distances of the rutted landscape. The highest SPR values mark the location of the ruts where the compaction extends to 20 cm or more in depth. The uncompacted soil outside and between the ruts exhibits lower SPRs.

4.5. Bulk density, BD

Data indicate that changes in BD due to vehicle compaction are affected by soil water content at the time of traffic and depth of measurement. Soil BD, both inside and outside a straight, dry soil rut at site C, was about 1.3 g cm^{-3} throughout the entire sampling depth (Fig. 11a). The uncompacted soil, outside a straight rut

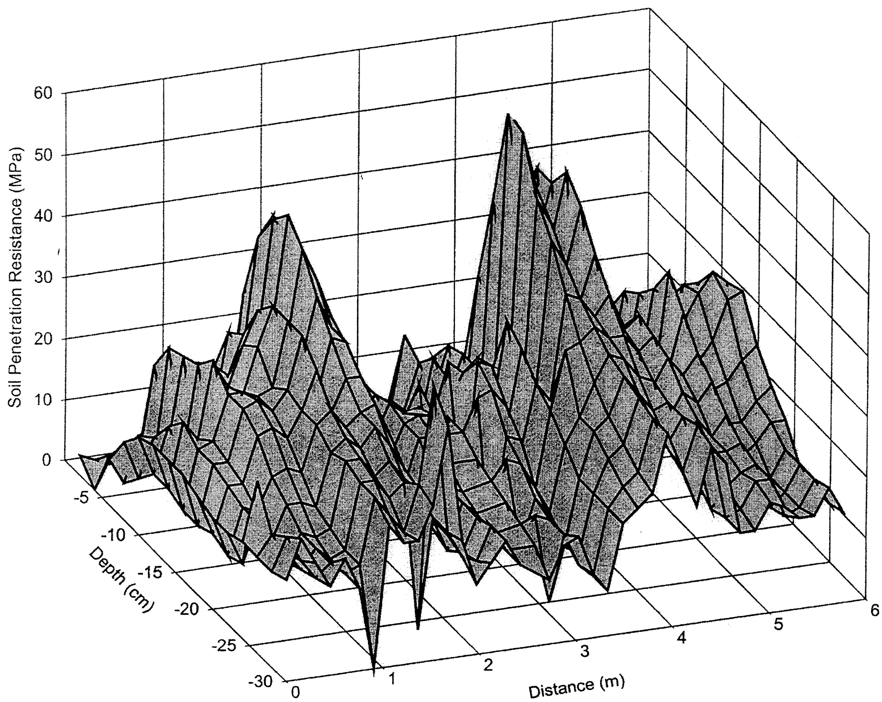

Fig. 10. The response surface created from SPR transect data collected across rut T-2, site E.

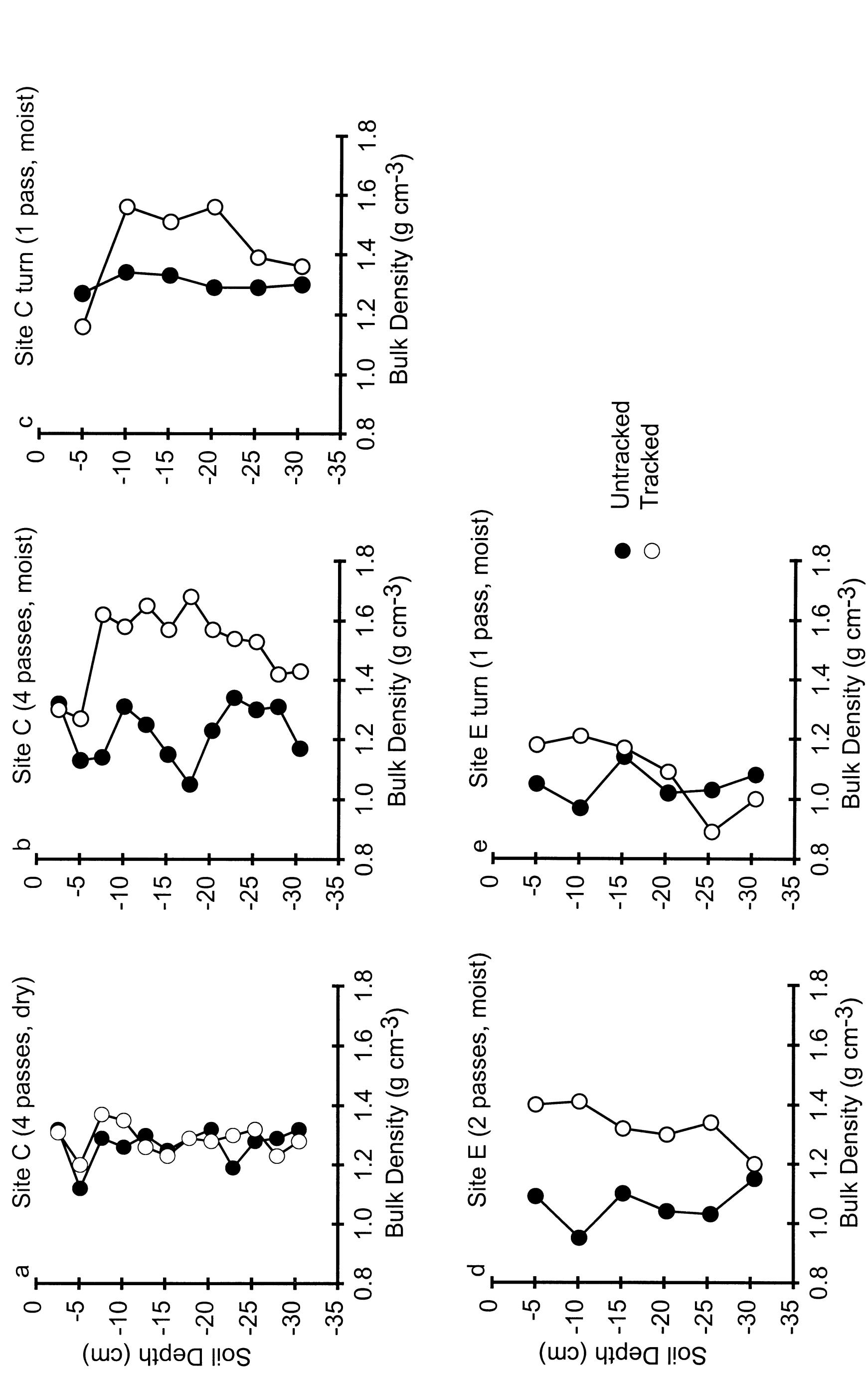

Fig. 11. Bulk density as a function of depth.

created on moist soil, also had an average BD of about 1.3 g cm^{-3} but consistently higher bulk densities were observed at all depths greater than 2.5 cm inside the rut (Fig. 11b). Measurements for a single-pass turning rut, revealed a similar, though less pronounced pattern with the greatest differences between rutted and uncompacted soil observed between 10- and 20-cm depth (Fig. 11c). We observed little difference between rutted and uncompacted soil at site C near the soil surface (2.5 cm).

Average bulk density outside straight ruts at site E was about 1.1 g cm^{-3} and showed little change with depth (Fig. 11d). In comparison, bulk density inside the adjacent rut, created on moist soil, was consistently higher (about 1.4 g cm^{-3}). Bulk density was greater in a turning rut at depths above 15 cm but greater in the uncompacted soil below 25-cm depth (Fig. 11e).

5. Conclusions

Data collected from December 1995 to April 1997 document the general smoothing of tank rut geometry that occurred over the 16-month study period. In summary, average rut surface profiles became significantly smoother with greatest rates of smoothing soon after tracking. Turning ruts, with the greatest amount of initial disturbance (highest average standard deviations in December 1995), smoothed more (had the greatest decrease in standard deviation over time) than straight-path ruts. Differences in the amount of smoothing observed among individual tank ruts suggest that the initial degree of soil compaction by tanks is variable and subsequent impacts of freeze–thaw cycles vary from rut to rut with greatest initial smoothing observed soon after tracking and for the deepest ruts.

The degree of compaction by tanks seems to be related to soil moisture content at the time of tracking. We observed comparatively more soil penetration resistance, higher bulk density, and lower hydraulic conductivity inside ruts at depths greater than about 2.5 to 5 cm when the tracks had been formed on moist soil. In contrast, we observed little difference between rutted and uncompacted soil when tracks were formed in dry soil.

Our findings also imply that soil is less compacted by tanks at the surface than deeper in the profile or that surface compaction does not persist. Less compaction may occur at the soil surface if water content is relatively low compared to deeper in the profile, at the time of tracking. Alternatively, compacted soil near the surface may be more strongly affected by forces such as wind, and wetting-drying and freeze–thaw cycles that fluctuate with higher frequency and amplitude at the soil surface than deeper in the soil profile.

Variation in the degree of compaction throughout the soil profile has important implications for potential erosion and its prediction because surface conditions will not resemble the compacted soil beneath it. Site managers might underestimate environmental damage or potential erosion based on the condition of the surface soil. Alternatively, the relatively uncompacted top few centimeters may significantly offset some of the impacts of compaction on water infiltration and runoff.

Acknowledgements

Funding for this research was provided by the Office of the Chief of Engineers, CERD-M, through the 6.1 Environmental Quality Technology Program, Conservation Pillar, BT-EC-B10 Project, *Soil Erodibility and Runoff Erosivity Due to Soil Freezing and Thawing*. The authors thank Maureen Kestler and Sally Shoop for technically reviewing the manuscript of this report, William Bowe, Russell Fitzgerald, Paul Mutch and Christopher Pannkuk for field assistance, and Peter Nissen at Yakima Training Center for assistance in the coordinating of fieldwork.

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